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LABORATORY TEST REQUIREMENTS FOR POST-FAILURE STRENGTH PROPERTIES OF ROCKS

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LABORATORY TEST REQUIREMENTS FOR POST-FAILURE STRENGTH PROPERTIES OF ROCKS

by

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SUMMARY

Due to the present day requirements it became essential to expand the testing capabilities of the Rock Mechanics Laboratory (RML). This includes the development of equipment and procedure to test rocks up to and beyond the failure. The described equipment and procedure were adapted after the review and evaluation of the various methods reported in the literature.

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INTRODUCTION

Investigation of heavier loaded rock mass structures indicates that regions of un-failed and failed rock coexist simultaneously in the rock mass. To carry out stability analysis on such standards, therefore, an adequate knowledge of rock behaviour is necessary, not only up to the failure but also beyond the failure.

To provide adequate rock properties data for the stability analyses of underground openings and support systems taken into account post-failure behaviour, an up-dating of the test capabilities of the Rock Mechanics Laboratory became essential.

It was considered important in analytic purposes that the testing equipment and procedure used to establish post-failure strength and deformation properties closely simulate the in situ loading and failure conditions.

This report provides a description of the work carried out to select the best suited test equipment and procedures. Various candidate test equipment described in the literature were reviewed and analyzed for this purpose. The offered advantages and disadvantages, the involved costs, the required development time and the complexity of the various candidate systems were evaluated and compared as part of the selection process.

The evaluation resulted in the adaption of a particular equipment system and development of testing procedures which will meet analytic requirements concerning post-failure rock deformational proportions and which are described in this report.

REVIEW OF STIFF TESTING PROCEDURES

It is a well recognized that during laboratory compressive test by the behaviour of brittle materials is affected by both the interaction of the testing machine and the properties of materials themselves.

The strength of the material corresponding to the failure point is usually called the maximum compressive strength. Provided the appropriate testing equipment and testing procedures are used, it is possible to determine the load carrying capacity of the rock specimen not only up to but also beyond the failure point. The load carrying capacity of the fractured specimen is usually referred to as post-failure compressive strength of the rock. The strength value corresponding to the horizontal portion of the stress-strain curve (Fig. 1) is usually called the residual compressive strength of the rock.

The analysis of post-failure behaviour of rock requires the so called "complete stress-strain curve". It is obtained by using specially designed stiff testing machines.

The completed literature survey revealed numerous methods that had been employed to convert conventional laboratory presses into stiff testing machines. The unique features of some of the stiff machines and of the associated testing procedures are briefly described below.

In 1962, Turner and Barnard succeeded in developing the first "stiff constant strain rate testing machine" to test composite structures of steel and concrete (1). Within a stiff frame the concrete specimens were compressed uniaxially with a specially designed hydraulic ram. The stiffness of the hydraulic system was achieved by using a ram with a large cross-sectional area and the very short stroke.

In 1966, Cook and Hojem successfully obtained complete stress-strain curves for rocks (2). With their system, rock specimens were prestressed by use of a hydraulic ram, but the final deformation of the specimen was achieved through the thermal contraction of the testing machine frame which had been preheated.

The test equipment of Hustrulid and Robinson was based on the same concept as the previous one. In this case, however, the final deformation of the initially prestressed specimen was achieved through the thermal elongation of an aluminium cylinder (3).

Wawersik and Brace used hydraulic rams, parallel to the rock specimen, to stiffen their laboratory press (4). The failure of the specimen was controlled by jacking up the rams when the axial load began to drop. The ultimate failure of the specimen was allowed to take place only after the application of several such loading and unloading cycles.

Encouraged by initial results, the development of stiff testing machines and testing techniques continued of an increased rate. Utilizing new concepts and equipment many research workers, managed to obtain complete stress-strain curves.

Ladanyi and Don approached the problem by using triaxial testing to combine purely hydraulic constraint with physical constraint (5). The physical constraint was realized by encasing the speciman, in addition to the rubber membrane, into a tissue-reinforced rubber tube having a slightly smaller inside diameter than the diameter of the specimen. Since this tube prevented the disintigration of the fractured specimen, it was possible to obtain data on the post-failure behaviour of the rock specimen.

A thousand-ton capacity stiff testing machine, with 2 GN/μ (11 x 10^6 lb/in.) stiffness rating, was built at USBM by Horino et al. (6). Three solid steel columns each with a diameter of 54 mm (2-1/8 in.) were used as stiffening elements. Placed parallel to the specimen, these columns were compressed simultaneously with the specimen by a two thousand-ton capacity conventional press.

The 2 MN (450,000 lb) capacity stiff testing machine of Hojem et al. utilizes the high bulk modulus properties of mercury. The contained mercury is compressed simultaneoulsy with the specimen (7). The stiffness of this machine was about 4 GN/μ (22 x 10^6 lb/in.).

The relative slow rate at which rock failure takes place has also made it possible to design and build electro-hydraulic servo controlled stiff machines. In 1971, Hudson et al. built the first such type of stiff testing machine (8). Complete stress-strain curves were obtained by using the output of the diametrical strain gauge as feed-back signal.

Perhaps the simplest, and at the same time the most versatile, stiff testing apparatus was designed by Ko and Gerstle (9). Disc-springs are used as stiffening elements. The stiffness of the test apparatus is adjustable by varying the number and the manner of stacking of the discs.

In general, these briefly described machines represent the major

equipment systems used for stiff testing. Other arrangements which can be found in the literature are the slightly modified versions of these previously described stiff testing machines.

Whatever, concept is used to provide a stiff testing apparatus, the ultimate aim in use is to obtain a complete stress-strain curve. The literature survey revealed that research workers, using various stiff testing machines, are obtaining two types of complete stress-strain curves. Typical shapes of both types are shown in Fig. 1.

The main difference between the two curves is that the slope of the post-failure region of the curves for Class I and Class II is negative and positive, respectively. Some of the authors classify the rock materials accordingly.

Explanations had been offered for the rather peculiar Class II material post-peak behaviour by the same authors. However, these views are not shared by everyone. For example, Ko and Gerstle have concluded that "since this Class II behaviour apparently has been observed only in servo-controlled machines, one can only speculate whether this effect is a machine characteristic rather than a fundamental material characteristic" (9).

SELECTED STIFF TESTING EQUIPMENT AND TEST PROCEDURE

The post-failure strength data are obtained in laboratory with the purpose of establishing empirical relationships which can be used for the stability evaluation of underground rock structures, for example of pillars. It is important that both the testing equipment and the testing procedure closely simulate the in situ loading and failure mechanisms.

The in situ condition of a room and pillar mining operation is demonstrated by Fig. 2(a). The rock mass around the openings is affected by the ground stresses. The original overburden load is assumed to be uniformly distributed. The deformation or the eventual failure of the pillar will cause redistribution of stresses. The probable stress distribution, following the failure of the pillar, is shown in Fig. 2(a). The testing analog which models the in situ condition is given in Fig. 2(b). The stiff testing arrangement, adapted from Ko and Gerstle, is based on this analog. The sketch of the test apparatus is shown in Fig. 2(c).

At RML the available 1.4 MN (3,000,000 lb) capacity press will be fitted to test rocks under both uniaxial and triaxial conditions. Because of the introduced stiffening elements, the effective capacity of the press will be reduced. Therefore, the maximum size of hard rock specimen that can be handled, even at a lower than the desired confining pressures, is BX (41 mm) diameter. The testing of standard NX size (54 mm diameter) specimen would require a press capacity of 3.6 MN (800,000 lb). However, the objective of the present phase of the testing program is to develop and to verify the post-failure testing procedure. For this reason the capability of testing BX size (41 mm diameter) specimens was judged adequate.

The simulation of in situ loading condition, achieved by the above stiff testing machine, represents only one requirement. The failure conditions also need to be simulated. The testing procedure recently developed by Kovari and Tisa will seemingly fulfill this requirement (10).

The simulation of failure conditions is achieved by the manual control of stress-strain correlation during the failure phase of the test. The schematic set-up of this continuous failure state triaxial test method is shown in Fig. 3. One of the employed XY recorder is used to mannually control the load during certain phases of the test. It is connected to the load and deformation transducers. The other XY recorder, which is connected to the axial load and confining pressure transducers, records the pressure data prevailing during the test.

Through manual control it is possible to change continuously the load, i.e., the axial and confining pressures, in such a manner that the specimen during the state of failure is being subjected continuously to plastic deformation. The procedure is explained with the aid of Fig. 4.

After Kovari and Tisa, the steps of the test, as demonstrated in Fig. 4(a), are:

1. Following the application of the predetermined confining pressure, σ_3, the specimen is axially loaded, at a given rate, until the imminent failure limit for the applied axial load and constant σ_3 confining pressure is reached. This is indicated by the deviation of stress--strain curve from the elastic straight line, marked by point A. (If at this point the test continued in the manner of a conventional triaxial test, then with a stiff testing apparatus the complete stress-strain curve, indicated in Fig. 4(a) by the dotted line, would be obtained.)

2. While maintaining the axial and confining pressures corresponding to point A, on the recorder-tracing-sheet from point A a straight line, with slope P (which is smaller than E), is drawn. This straight line sets the predetermined stress-strain relation during the next step of the test.
3. The axial load, σ_1, is increased at the given rate, while the confining pressure, σ_3, is manually increased in such way that the recording pen of the XY recorder follows the predetermined straight line.
4. At any desired point B of the straight line, while the prevailing confining pressure is kept constant, the continuous failure of the specimen is allowed to take place. During this phase of the test with a testing machine the specimen is compressed at decreasing axial stresss until the residual strength is reached. This state is indicated by the beginning of a horizontal plateau in the stress-strain curve, as marked by point C.
5. While maintaining the axial and confining pressures corresponding to point C, on the recording-tracing-sheet, from point C a straight unloading line (with approximate slope angle of negative P) is drawn.
6. The confining pressure, σ_3, is manually reduced in such way that the recording pen follows the straight unloading line.

The axial load and confining pressure data, corresponding to the above test phases, are recorded by the second XY recorder. A typical data recording is shown in Fig. 4(b). Curve A - B represents the stresses in the peak strength region. After touching the peak strength envelope the curve deviates increasingly from it. Curve C - O corresponds to the residual strength region. Kovari and Tisa concluded that curve C - O practically coincides with the residual strength envelope.

The continuous failure state triaxial test method offers several advantages. The strength limits of the rock, i.e., peak and residual strength envelopes can be determined with a limited number of specimens. It is possible to obtain entire sections of the strength limit curves, therefore, the procedure provides more qualitative data on the strength properties. Furthermore, the test method provides data on the relationship between the strength and plastic deformation.

The advantages offered by the test procedure can perhaps be best demonstrated if the test procedure is compared with the failure mechanism of a pillar. Due to the excavation of rooms the original in situ stresses on a

cylindrical element in the centre line of the pillar, shown in Fig. 4(c), change to initial pillar stresses, denoted by σ_1^P and σ_3^P. The application of the confining pressure σ_3 and then the axial load σ_1, represented in Fig. 4(b) by stress path O - A, is a simulation of initial pillar stresses due to opening development.

The stress redistribution in the surrounding rock mass takes time. Consequently, with time more and more load is transferred to the pillar which causes pillar deformation. The axial stress on the cylindrical element, as shown in Fig. 4(d), increases by the value of σ_1^V. Meantime, due to the Poisson's effect, the confining pressure also increases by the value of σ_1^V. This process is simulated in the test by the simultaneously increased axial and confining pressures, represented in Fig. 4(b) by the steeply ascending portion of the stress path A - B.

The load on the pillar increases continuously until the peak carrying capacity of the pillar is reached. The load increase is accompanied by increased pillar deformation. In terms of stresses, the peak carrying capacity is denoted by σ_1^F and σ_3^F in Fig. 4(e), which are the peak values. The initiated pillar failure occurers under these stress conditions. The stress condition in Fig. 4(b) is represented by the point where stress path A - B touches the peak strength envelope. The pillars usually fail in the manner of gradual disintegration. Initial failure is indicated by increased deformation and surface spalling. Sudden pillar failure could also occur, however, it is a special case and results in rock burst situations.

Passed its peak strength the carrying capacity of the pillar decreases. The rate of decrease depends on the material properties, which control the plastic deformability, and also on confining pressure conditions that prevail. In any case, due to the fracturing caused by the failure, the pillar material becomes more plastic. The pillar failure for a while might only be evident from an increased rate of deformation with small loss in carrying capacity. This transition state is represented in Fig. 4(b) by the lost portion of stress path A - B. The short term transition state is followed by a sudden drop in the carrying capacity, although the pillar might appear to be intact. The change in stress configuration, as it is simulated by the test, is reflected in Fig. 4(b) by the stress path B - C. The schematic illustration of the transition state is given in Fig. 4(f). In

comparison with the failure stresses of σ_1^F and σ_3^F, the axial stress σ_1^T decreases while the lateral stress σ_3^T increases.

Point C in Fig. 4(b) corresponds to the maximum residual axial and confining stress values, denoted in Fig. 4(g) by σ_1^R and σ_3^R, respectively. The pillar disintegration process is simulated in the test by the continuously controlled decrease of confining pressure, represented in Fig. 4(b) by stress path C - O.

REFERENCES

1. Turner, P.W. and Barnard, P.R. "Stiff constant rate testing machines"; The Engineer, vol 214, No. 5557; 1962.

2. Cook, N.G.W. and Hojem, J.P.M. "A rigid 50-ton compression and tension testing machine"; S. Afr. Mech. Eng., vol 16; 1966.

3. Hustrulid, W. and Robinson, F. "A simple stiff machine for testing rock in compression"; Proc Fourteenth Symp. on Rock Mech., Am. Soc. Civ. Engrs.; 1973.

4. Wawersik, W.R. and Brace, W.F. "Post-failure behaviour of a granite and diabase"; Rock Mech., vol 3; 1971.

5. Ladanyi, B. and Don, Nguyen "Study of strains in rock associated with brittle failure"; Proc 6th Can. Rock Mech. Symp., Mines Branch, Department of Energy, Mines and Resources; 1971.

6. Horino, F.G., Brady, B.T., Duvall, W.I. and Hooker, V.E. "A thousand-ton capacity stiff testing machine"; RI 7624; U.S. Bureau of Mines.

7. Hojem, J.P.M., Cook, N.G.W. and Heins, C. "A stiff, two maga-newton testing machine for measuring the work-softening behaviour of brittle materials"; S. Afr. Mech. Eng., vol 25; 1975.

8. Hudson, J.A., Brown, E.T. and Fairhurst, C. "Optimizing the control of rock failure in servo-controlled laboratory tests"; Rock Mech., vol 3; 1971.

9. Ko, H.Y. and Gerstle, K.H. Unpublished report; 1974.

10. Kovar, K. and Tisa, A. "Multiple failure state and strain controlled triaxial tests"; Rock Mech., vol 7; 1975.

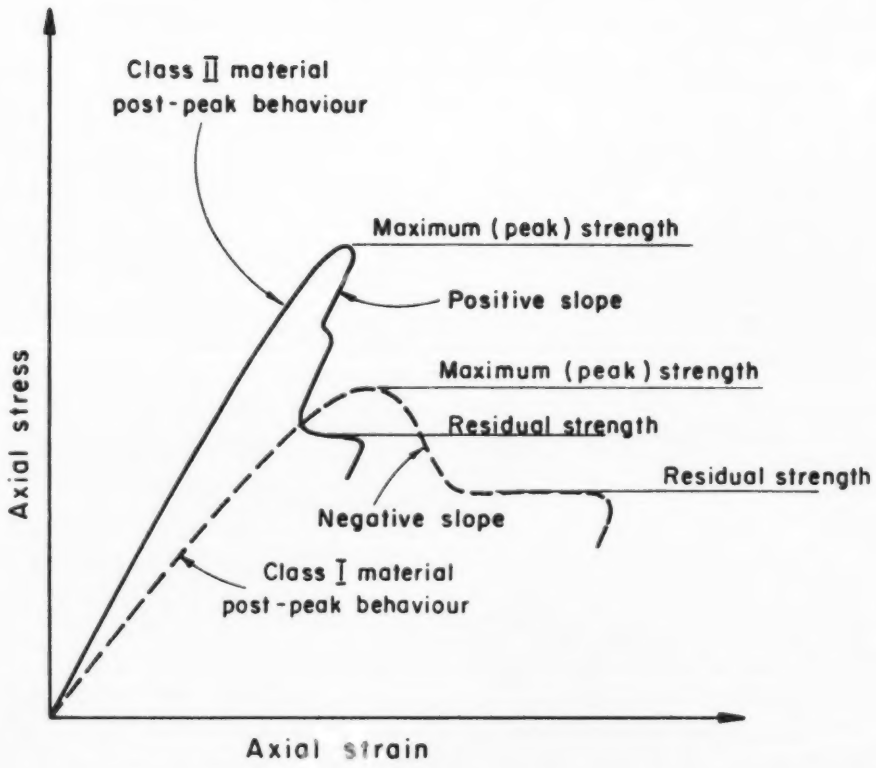

Fig. 1 - Typical complete stress-strain curves

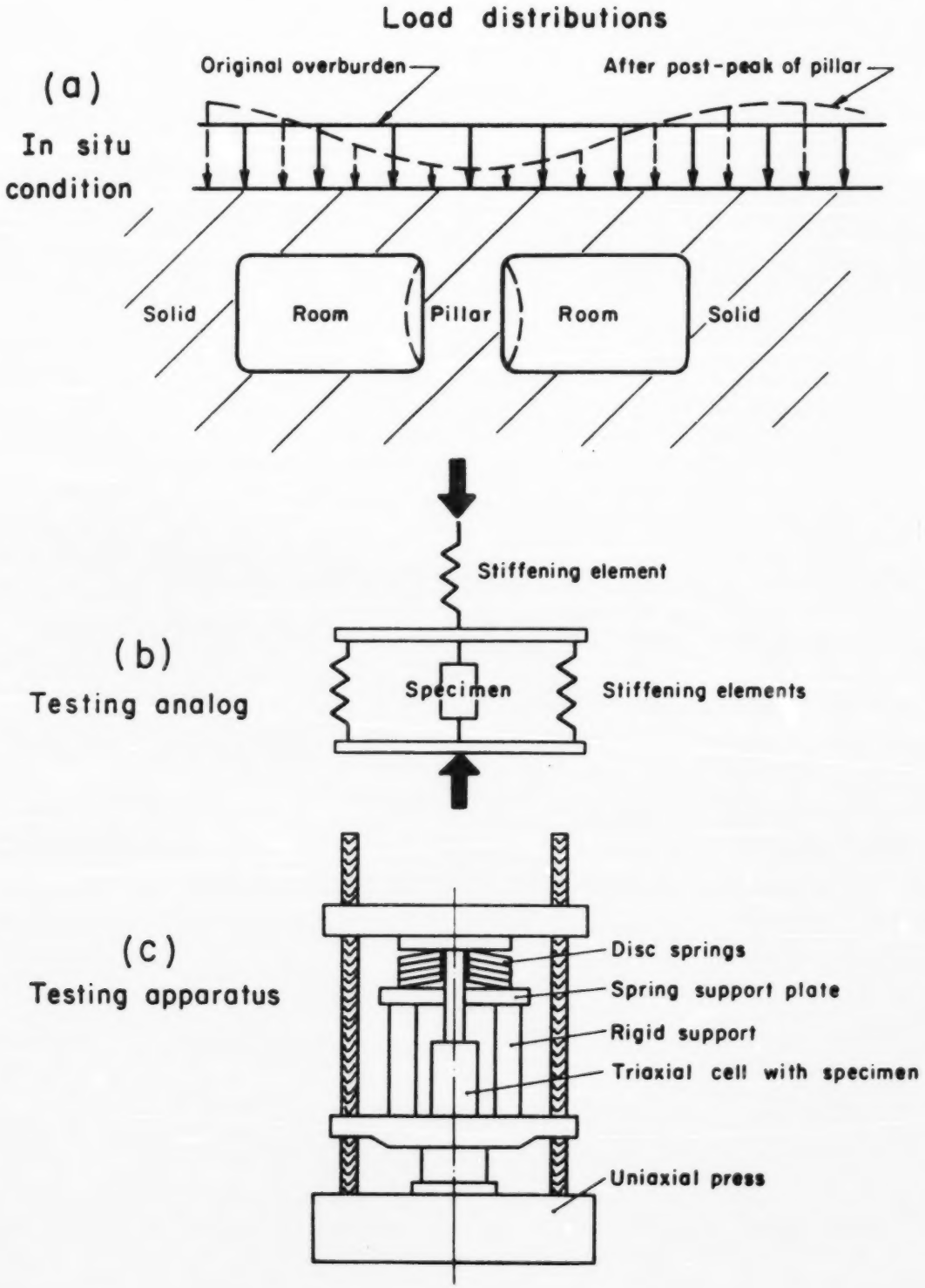

Fig. 2 - Selected stiff testing equipment

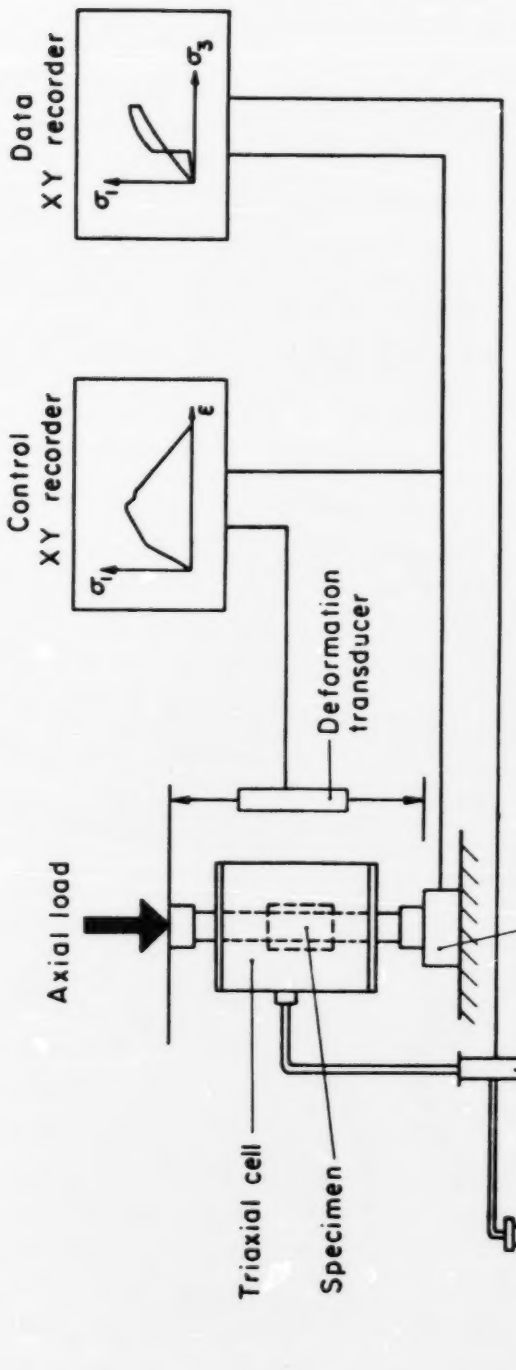

Fig. 3 - Arrangement for continuous failure state triaxial test

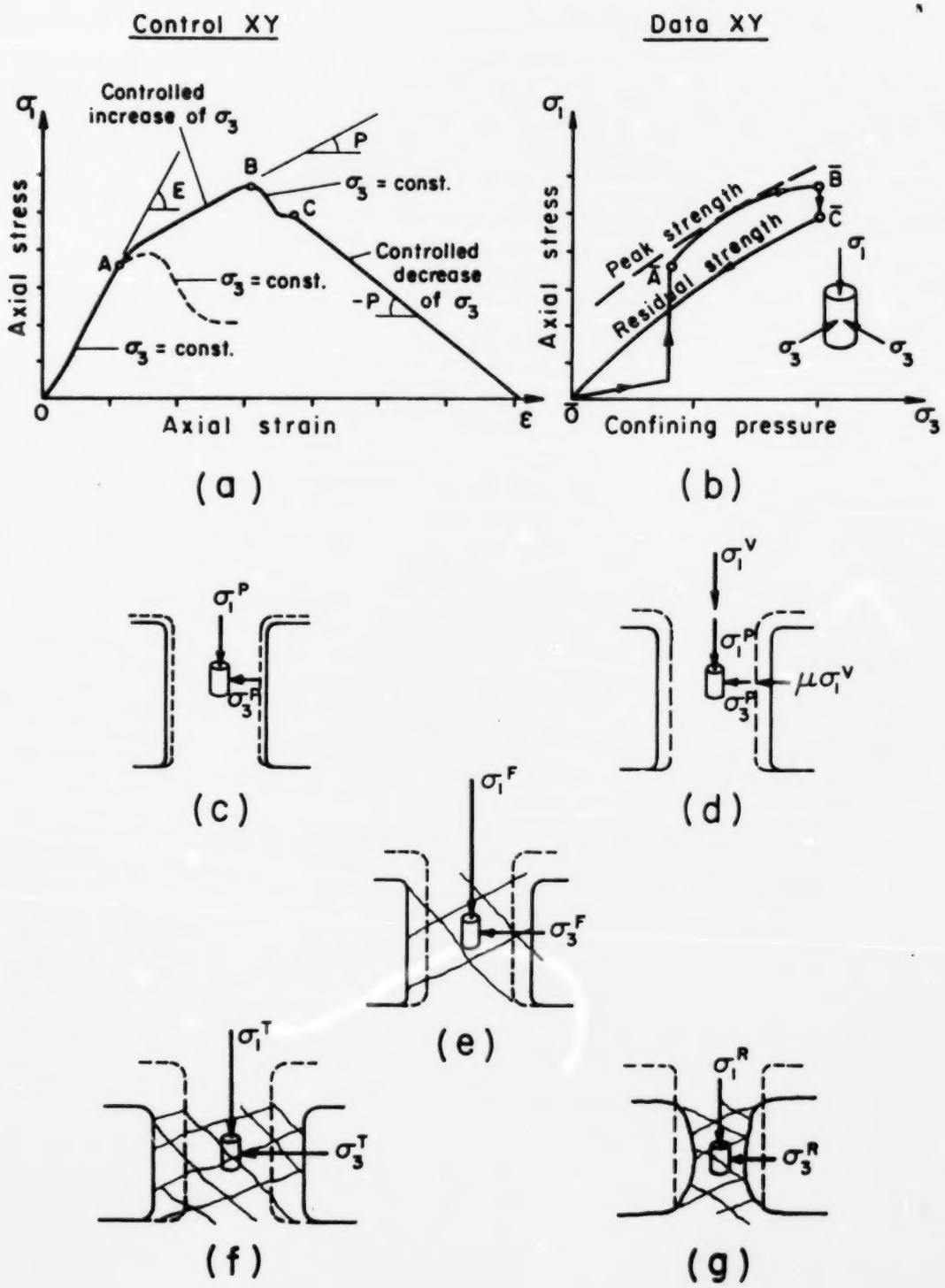

Fig. 4 - Selected test procedure